Paper

Planning System for Multi-Agent Based Reconfigurable Fixtures

Wojciech Szynkiewicz

Abstract—This paper describes a concept of the planning system for self adaptable, reconfigurable fixtures composed of mobile locators (robotic agents) that can freely move on a bench and reposition below the supported part, without removing the part from the fixture. The main role of the planner is to generate the admissible plan of relocation of the mobile agents. A constrained nonlinear optimization problem is formulated to find the optimal locations for supporting heads.

Keywords—fixture planner, multi-agent system, optimization.

1. Introduction

The fixture planning system is an important element in computer aided process planning systems [1]. A fixture is a device for locating, constraining, and adequately supporting a workpiece during a manufacturing operation. Fixturing, like grasping seeks arrangements of contacts that restrict the possible motions of a given part. An important factor in fixture design is to optimize the fixture layout, i.e., positions of mobile locators, so that workpiece deformation due to clamping and machining forces is minimized [2], [3]. In this paper we consider the manufacturing process consists of milling (contouring) of thin-sheet aluminium parts for aircrafts and automotive bodies. Workpiece deformation is unavoidable due to its elastic nature, and the external forces impacted by the clamping actuation and machining operations. When severe part displacement is expected under the action of imposed machining forces, supports are needed and they should be placed below the workpiece to prevent or constrain deformation.

The existing fixtures for thin-walled workpieces like sheet-metal parts with complex surface geometries are:

- large mould-like fixtures,
- modular flexible fixture systems (MFFSs),
- single structure flexible fixture systems (SSFFS).

The fixtures traditionally used in manufacturing of thin-sheet metal parts are large moulds reproducing the shape of the skin to be supported, but this type of fixture is part specific and not reconfigurable. Usually, the mould surface is equipped with vacuum suction chambers and channels for holding the skin.

The MFFSs can be further classified on the basis of their adjusting mechanism:

- Partially reconfigurable with limited number of supports that can be manually relocated.
- Adjusted by separate devices, e.g., robot manipulators.
- Self-reconfigurable with a matrix of support elements with embedded actuators (in each locator/clamp).

It should be noted that all such fixtures still require some human intervention to reconfigure. Various MFFSs have been proposed [4]–[6], but their usage for thin-walled parts fixturing is rather limited. Since fixturing requirements vary during the different machining operations required on a single part, it becomes necessary to reposition the supports, interrupting the production process. MFFSs can be adapted to various parts but their initial cost is often high while configuration is complex and time consuming.

One way to avoid this problem is to use an SSFFS of the pin-bed type, with a matrix of supports, which provides support comparable to a mould-like fixture. The main disadvantages are high cost, and a lack of modularity, which makes them difficult or inefficient to use for parts of differing sizes.

Robotic fixtureless assemblies (RFAs) replace traditional fixtures by robot manipulators equipped with grippers that can cooperatively hold the workpiece [7], [8]. Using RAFs different parts can be manufactured within one work-cell and transitions to other workpieces can be done relatively quickly. However, RAFs have their drawbacks such as high complexity, limited number of robots (and thus holding grasps), and high dependence on software.

The concept described in this papers merges the advantages of RFAs with those of MFFSs, namely: ability to distribute the support action, adaptability to part shapes in a larger range, and high stiffness of the provided support. In our case each fixture element referred to as a physical agent is composed of a mobile robot base, a parallel kinematic machine (PKM) fixed to the mobile platform, an adaptable head with phase-change fluid and an adhesion arrangement, to sustain the supported part perfectly adapting to the part local geometry. The mobility of each support agent and the possibility for the agents to group in regions where some manufacturing operation is being executed results in higher flexibility with lower number of support agents.

Proper fixture design is crucial to product quality in terms of precision, accuracy, and surface finish of the machined parts. Therefore, the research devoted to fixture optimization is quite extensive [2], [9], [10]. Various techniques have been proposed for optimization of fixture layout by formulating different objective functions to determine the location of fixturing supports. In the research for compliant sheet metal parts, Menassa and De Vries [2] use a finite element model of the workpiece to model the deformation, and determine fixture locations by optimizing an objective that is a function of the deformations at the nodes. The design variables are three fixture locators on primary datum as required by the 3-2-1 principle. In [11] an optimization algorithm to obtain the optimal number and location of clamps that minimize the deformation of compliant parts is proposed. Cai *et al*. [9] propose the N-2-1 fixture layout principle for constraining compliant sheet metal parts. This is used instead of the conventional 3-2-1 principle to reduce deformation of sheet-metal parts. They present algorithms for finding the best N locating points such that total deformation of a sheet metal is minimized. They use a finite element model of the part with quadratic interpolation, constraining nodes in contact with the primary datum to only in-plane motion. Nonlinear programming is utilized to obtain the optimal fixture layout. DeMeter [10] introduces a fast support layout optimization model to minimize the maximum displacement-to-tolerance ratio of a set of part features subject to a system of machining loads. The speed-up of the optimization is obtained by a reduced stiffness matrix approach. Most of the previous research related to fixture modeling and design considers fixture in static conditions.

In this paper we propose a concept of the planning system for self adaptable, reconfigurable fixtures composed of mobile support agents. The main role of the planner is to generate the admissible plan of relocation of the mobile agents. It has to find the optimal locations for the supporting heads and the trajectories of the mobile bases that provide continuous support in close proximity to the tool and very high speeds during the relocation phases. In this paper a constrained optimization problem is formulated to find the optimal locations for heads that minimize the given objective function. The constraints to this optimization problem are geometric in nature. The size and dimension of the supporting head are taken into account.

The rest of the paper is organized in the following manner. In Section 2 the concept of a self adaptable reconfigurable fixture system is presented. Section 3 describes an admissible head placement planning problem. In Section 4 head location placement problem is formulated as a constrained nonlinear optimization problem. A numerical example is presented in Section 5. In Section 6 some concluding remarks are presented.

2. Self-Adaptable Reconfigurable Fixture System

Flexible fixture system is composed of mobile robotic agents that can freely move on a bench and reposition below the supported part as shown in Fig. 1. It is assumed that the workpiece is held in position by a subset of locators (not shown in this figure) that remain largely static during the cycle. The remaining agents are highly mobile and change locations to provide additional support in areas affected by the machining process. As mentioned before each support robot consists of a mobile base, a PKM, and an adaptable head. Two mobile agents alternatively supporting a thin sheet while a machine tool with a milling cutter is contouring the workpiece. To simplify motion planning and collision avoidance we assume that the robots move along parallel trajectories. Heads adapt to the local geometry of the workpiece to support it at every repositioning. Adaptation is at two levels: head rotation, to match the approximate orientation of the part surface normal, and head surface deformation, to match the local part surface geometry.

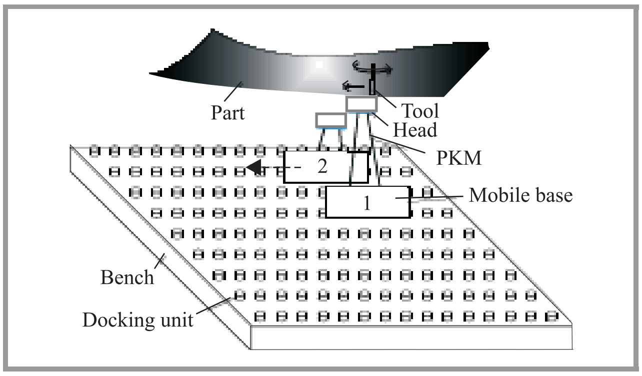

Fig. 1. Self-adaptable reconfigurable fixture system.

The overall goal is to develop the planner, which on the basis of CAD geometric data about the workpiece, representing its state before and after machining, will generate the plan of relocation of the mobile bases and the manip-

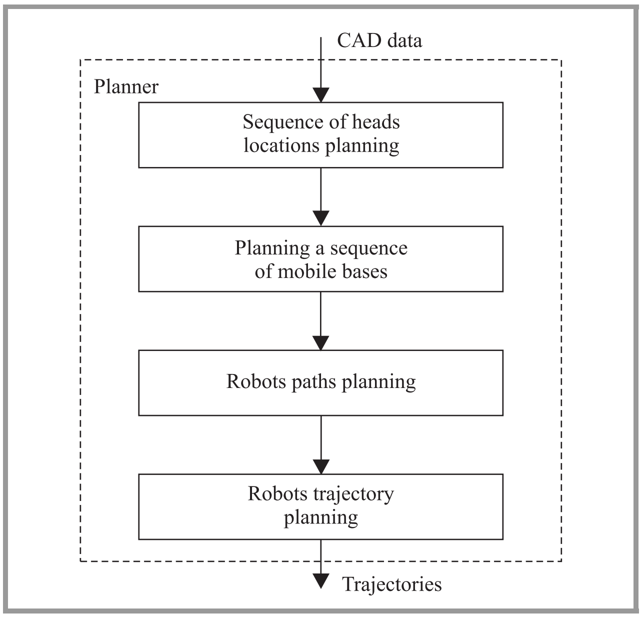

Fig. 2. Planner decomposition.

ulators. Planning process is decomposed into four phases: planning a sequence of feasible head placements, planning a corresponding sequence of mobile platforms locations, path planning for mobile platforms and PKMs, trajectory planning for mobile platforms and PKMs (Fig. 2). Obtaining a feasible sequence of head locations is the most difficult part of the planning process. In the paper we will present an approach to solve this problem.

3. Feasible Head Placement

3.1. Geometric Description

We assume that the workpiece contour is modeled as a two-dimensional (2D) simple closed polygonal chain with a given number of linear segments. Closed polygonal curve P in 2D space is described as the ordered set of vertices:

$$P = \{p_1, \dots, p_{M+1}\} = \{(x_1, y_1), \dots, (x_{M+1}, y_{M+1})\}, \quad (1)$$

where the last vertex coincides with the first one, i.e., $p_{M+1} = p_1$. The workpiece boundary consists of M line segments. Each line segment can be described by the following equation:

$$y = a_j x + b_j, \quad j = 1, \dots, M. \quad (2)$$

The coefficients a_j and b_j of the line are calculated from the coordinates of the end points p_j and p_{j+1}:

$$a_j = \frac{y_{j+1} - y_j}{x_{j+1} - x_j}, \qquad b_j = y_j - a_j x_j. \quad (3)$$

Hereafter, we assume that both heads are identical. The head R is an equilateral triangle

$$R_i = \{r_1, \dots, r_4\}, \quad \text{where } r_4 = r_1. \quad (4)$$

Edge length of the triangle is equal to L.
We assume that the head configuration is specified by $q = (x, y, \theta)^T$, where x, y are Cartesian coordinates relative to a fixed reference coordinate frame and θ is the orientation angle. Configuration space (C-space) of the head is $\mathbb{Q} = \mathbb{R}^2 \times S^1$, where S^1 is the unit circle. Moreover, we explicitly represent the normal vectors for each edge of

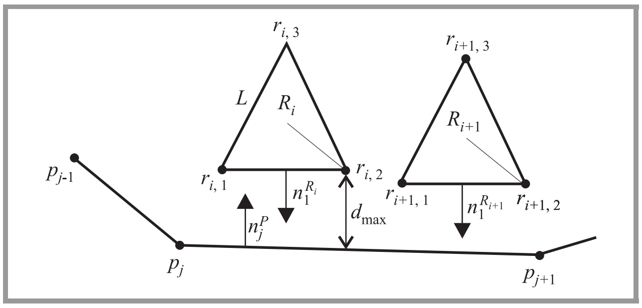

Fig. 3. Geometric constraints for head placement

the head and line segment of the part contour. We denote these normal vectors by $n_k^{R_i}$ for the normal to edge k of the head location i and n_j^P for the normal to j line segment of the polygonal curve P. It should be noted, that for the head edges depend on the orientation θ (but do not depend on x, y-coordinates). In Fig. 3 geometric constraints are depicted.

3.2. Constraints

Four main conditions need to be satisfied for every feasible head placement, R_i:

- The biggest distance between the head and the working profile (workpiece contour) has to be d_{max} to avoid vibrations during contouring.
- The head surface must not come in contact with the tool.
- The maximum allowable distance between two subsequent head locations has to D_{max}.
- The heads must not overlap each other.

To satisfy these conditions we must to know the minimum and maximum distance between two objects. Minimum distance calculation is essential for collision detection, if the the minimum distance between to objects is zero, then they are in contact. The distance between two polytopes (in 2D polygons) Q and P is defined as

$$d_m(P, Q) = \min_{p \in P, q \in Q} \|p - q\|. \quad (5)$$

Expression (5) can be reformulated in terms of the Minkowski difference of two polytopes, i.e.,

$$P \ominus Q = \{z | z = p - q, p \in P, q \in Q\} = Z. \quad (6)$$

Using Eq. (6) we can rewrite Eq. (5) as

$$d_m(P, Q) = \min_{p \in P, q \in Q} \|p - q\| = \min_{z \in P \ominus Q} \|z\| \quad (7)$$

and we have reduced the problem of computing distance between two polytopes to the problem of computing the minimum distance from one polytope to the origin of the coordinate frame. The Minkowski difference of two convex polytopes is itself convex polytope. Since $Z = P \ominus Q$ is a convex set, and since the norm, $\|z\|$, is a convex function, $\hat{z} = \arg\min_{z \in Z} \|z\|$ is unique. However, p and q to achieve this minimum are not necessarily unique. To compute the minimum distance we use well-known GJK algorithm [12]. The Euclidean distance d from point $p_k = (x_k, y_k)^T$ to the line segment $y = a_j x + b_j$ can be calculated by the following expression:

$$d = \frac{|y_k - a_j x - b_j|}{\sqrt{1 + a_j^2}}. \quad (8)$$

The biggest allowable distance between the head and the working profile has to be d_{max} to avoid vibrations during contouring

$$d_i(P,R_i) \leqslant d_{max}, \quad i,=1,\ldots,N-1 \tag{9}$$

This means that the distance between workpiece contour and the closest edge $E_k^{R_i}$ of the head R_i to the contour segment must not be greater than d_{max}. The heads must not overlap each other

$$\mathrm{int}(R_i) \cap \mathrm{int}(R_{i+1}) = \emptyset, \quad i,=1,\ldots,N-1\,, \tag{10}$$

where $\mathrm{int}(R_i)$ denotes the interior of the triangle. However, two heads may contact each other. Contact between two heads can occur only when orientation θ satisfies the following condition

$$\begin{gathered}(r_{i,j-1}(\theta_i) - r_{i,j}(\theta_i)) \cdot n_k^{R_{i+1}}(\theta_{i+1}) \geqslant 0 \wedge \\ (r_{i,j+1}(\theta_i) - r_{i,j}(\theta_i)) \cdot n_k^{R_{i+1}}(\theta_{i+1}) \geqslant 0, \\ j,k=1,2,3;\; i,=1,\ldots,N-1\,.\end{gathered} \tag{11}$$

If this condition satisfied there is a contact between edge, $E_k^{R_{i+1}}$, of the head R_{i+1} and vertex $r_{i,j}$ of the head R_i. At extreme, the vertices $r_{i,j}$ and $r_{i+1,k}$ coincide, while at the other extreme, vertices $r_{i,j}$ and $r_{i+1,k+1}$ coincide.
Analogously, when the condition

$$\begin{gathered}(r_{i+1,j-1}(\theta_{i+1}) - r_{i+1,j}(\theta_{i+1})) \cdot n_k^{R_i}(\theta_i) \geqslant 0 \wedge \\ (r_{i+1,j+1}(\theta_{i+1}) - r_{i+1,j}(\theta_{i+1})) \cdot n_k^{R_i}(\theta_i) \geqslant 0, \\ j,k=1,2,3;\; i,=1,\ldots,N-1\end{gathered} \tag{12}$$

is satisfied there is a contact between edge, $E_k^{R_i}$, of the head R_i and vertex $r_{i+1,j}$ of the head R_{i+1}. Again, at extreme, the vertices $r_{i+1,j}$ and $r_{i,k}$ coincide, while at the other extreme, vertices $r_{i+1,j}$ and $r_{i,k+1}$ coincide. The head surface must not come in contact with the tool

$$d_i(P,R_i) \geqslant d_{min}, \quad i=1,\ldots,N\,. \tag{13}$$

4. An Optimization Problem

Planning a sequence of the supporting heads locations can be formulated as a constrained optimization problem. The optimization model is presented as follows:

- Design variables. The head locations $R_i(x,y,\theta)$, $(i=1,\ldots,N)$. Hence, the vector of variables is defined as follows

$$\boldsymbol{x} = [x_1, y_1, \theta_1, \ldots, x_N, y_N, \theta_N]^T\,.$$

- Min-max nonlinear optimization problem:

$$\min\,\max f_i(\boldsymbol{x}), \quad i=1,\ldots,N, \tag{14}$$

  where $f_i(x) = d_i^2(P,R_i)$ is the squared distance of the head $R_i, i=1,\ldots,N$ to the contour P. The following motivation is behind this form the objective function: the closest distance of the support head to the working contour the lowest vibrations may occur.

- Constraints. All previously defined constraints can be described in general form

$$\boldsymbol{g}(\boldsymbol{x}) \leqslant 0\,. \tag{15}$$

  Moreover, the following linear inequality constraints must be satisfied

$$A\boldsymbol{x} - b \leqslant 0\,, \tag{16}$$

  where the entries of the matrix A and the vector b are calculated according to Eq. (3). It means that the heads in each location must be inside the region limited by the working contour.

To solve the nonlinear min-max optimization problem Eqs. (14)–(16) in an efficient and robust way we transform this problem into a special nonlinear programming problem (NLP). We introduce one additional variable, z, and N additional nonlinear inequality constraints in the form

$$f_i(\boldsymbol{x}) - z \leqslant 0, \quad i=1,\ldots,N\,. \tag{17}$$

The following equivalent optimization problem can be defined

$$\min z \tag{18}$$

subject to the constraints of the original problem Eqs. (14)–(16) and the additional constraints (17). To solve this problem an efficient existing nonlinear programming techniques can be used.

5. A Numerical Example

Let us consider a workpiece which boundary is shown in Fig. 4. This contour can be described as a closed

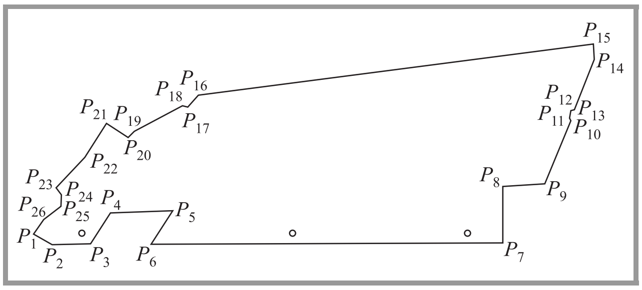

Fig. 4. Workpiece boundary.

polygonal chain. The vertices are enumerated in anticlockwise direction and their Cartesian coordinates are given in Table 1. The following values of the parameters are selected: edge length of the head $L = 70$ mm, maximum distance $d_{\max} = 20$ mm, minimum distance $d_{\min} = 1$ mm of the head to the workpiece contour, and maximum distance between two heads $D_{\max} = 20$ mm. The number of variables in this specific problem is equal to $N = 268$ that corresponds to 89 head locations. The number of nonlinear inequality constraints is 882 and linear inequality constraints is 26. The code solving an optimization

Table 1
Vertices of the contour

Point	x [cm]	y [cm]	Point	x [cm]	y [cm]
P_1	8.30	75.54	P_{14}	283.96	162.36
P_2	16.51	70.28	P_{15}	284.01	169.15
P_3	36.07	70.33	P_{16}	88.67	143.77
P_4	45.83	85.86	P_{17}	83.90	138.10
P_5	76.29	87.22	P_{18}	81.54	138.94
P_6	65.50	70.42	P_{19}	57.26	126.08
P_7	239.31	70.92	P_{20}	54.52	123.28
P_8	239.31	99.13	P_{21}	43.82	130.17
P_9	259.93	100.08	P_{22}	32.99	113.25
P_{10}	272.51	131.75	P_{23}	19.14	98.38
P_{11}	271.78	132.71	P_{24}	21.29	94.92
P_{12}	273.09	136.31	P_{25}	21.24	89.02
P_{13}	274.49	136.97	P_{26}	12.93	82.78

problem was implemented in Matlab. The specific optimization algorithm used is the constrained nonlinear programming function *fmincon()* from Matlab [13]. The main problem is to find a feasible starting point for the optimization algorithm, which satisfies all constraints. The choice of the starting point strongly influence the performance. Typically, to solve this optimization problem 20-25 itera-

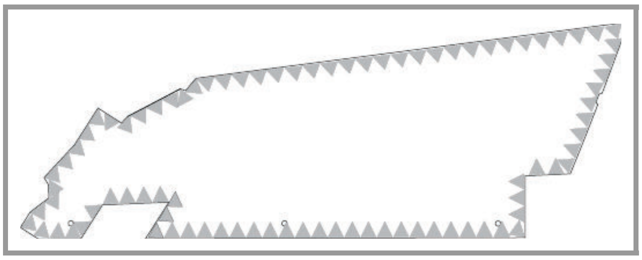

Fig. 5. An admissible head placement.

tions are required. The value of termination tolerance is equal to $1 \cdot 10^{-6}$. The preliminary optimization results are shown in Fig. 5. This figure presents the admissible head placement obtained by solving NLP problem.

6. Summary and Conclusion

In this paper, we presented a methodology for modeling and optimization for self adaptable, reconfigurable fixtures supporting thin sheet metal parts to minimize part dimensional deformation during milling. Compliant sheet metal parts are widely used in various manufacturing processes including automotive and aerospace industries. The concept of the multi-layer planning system is proposed. The most difficult part of the planning process, namely, a head placement problem is considered. To find a feasible plan of a sequence of supporting head locations nonlinear programming problem is solved. Finally, a numerical example is used to illustrate the feasibility of this method. In future work, we will develop a complete planner including trajectory planning of the mobile bases and PKMs.

Acknowledgements

This work was partially supported by the Polish Ministry of Science and Higher Education through grant No. N N 514 1287 33.

References

[1] A. Vidal, M. Alberti, J. Ciurana, and M. Casadesús, “A decision support system for optimising the selection of parameters when planning milling operations”, *Int. J. Mach. Tool Manu.*, vol. 45, no. 2, pp. 201–210, 2005.

[2] R. Menassa and W. De Vries, “Optimization methods applied to selecting support positions in fixture design”, *ASME J. Eng. Ind.*, vol. 113, no. 4, pp. 412–418, 1991.

[3] S. Vallapuzha, E. C. De Meter, S. Choudhuri, and R. P. Khetan, “An investigation of the effectiveness of fixture layout optimization methods” *Int. J. Mach Tool Manu.*, vol. 42, no 2, pp. 251–263, 2002.

[4] M. N. Sela, O. Gaudry, E. Dombre, and B. Benhabib, “A reconfigurable modular fixturing system for thin-walled flexible objects” *Int. J. Adv. Manuf. Technol.*, vol. 13, no. 9, pp. 611–617, 1997.

[5] B. Shirinzadeh and Y. Tie, “Experimental investigation of the performance of a reconfigurable fixture system”, *Int. J. Adv. Manuf. Technol.*, vol. 10, no. 5, pp. 330–341, 1995.

[6] K. Youcef-Toumi, W. Liu, and H. Asada, “Computer-aided analysis of reconfigurable fixtures and sheet metal parts for robotics drilling”, *Rob. Comp.-Integr. Manu.*, vol. 4, pp. 3–4, pp. 387–393, 1988.

[7] Z. M. Bi and W. J. Zhang, “Flexible fixture design and automation: review, issues and future directions”, *Int. J. Prod. Res.*, vol. 39, no. 13, pp. 2867–2894, 2001.

[8] Y. Kang, Y. Rong, J. Yang, and W. Ma, “Computer-aided fixture design verification”, *Assembly Autom.*, vol. 22, no. 4, pp. 350–359, 2002.

[9] W. Cai, S. J. Hu, and J. X. Yuan, “Deformable sheet metal fixturing: principles, algorithms, and simulations”, *T ASME, J. Manuf. Sci. Eng.*, vol. 118, no. 3, pp. 318–324, 1996.

[10] E. C. DeMeter, “Fast support layout optimization”, *Int. J. Mach. Tools Manuf.*, vol.38, no. 10–11, pp. 1221–1239, 1998.

[11] M. R. Rearick, S. J. Hu, and S. M. Wu, “Optimal fixture design for deformable sheet metal workpieces”, *Trans. NAMRI/SME*, vol. 21, pp. 407–412, 1993.

[12] E. Gilbert, D. Johnson, and S. Keerthi, “A fast procedure for computing the distance between objects in three-dimensional space”, *IEEE J. Robot. Autom.*, vol. 4, pp. 193–203, 1988.

[13] Matlab. *Optimization Toolbox User’s Guide*. The MathWorks, Inc., 2009.

Wojciech Szynkiewicz received the Ph.D. degree in robotics in 1996 from the Warsaw University of Technology (WUT). He is an Assistant Professor employed by the Institute of Control and Computation Engineering of WUT. From 1999 to 2003 he was the Deputy Director and Secretary to the Scientific Council of the Research Center for Automation and Information-Decision Technology-CATID. His research activities concentrate on multi-robot/multi-agent systems, motion planning, autonomous mobile robots, robot controller structures, and real-time and distributed systems. He works on sensor-based motion planning and control algorithms for multi-robot systems, including service, personal and mobile robots.
email: W.Szynkiewicz@ia.pw.edu.pl
Institute of Control and Computation Engineering
Warsaw University of Technology
Nowowiejska st 15/19
00–665 Warsaw, Poland